5

chapter

REFRIGERATED STORAGE

INTRODUCTION

Refrigerated foods have become a mainstay in developed countries due to the prevalence of refrigerators in every household. The availability of chilled display cabinets and development of refrigerated storage capacities, particularly during transport, have also spurred growth of the refrigerated foods market. In the 1970s and 80s, food manufacturers introduced a wide variety of refrigerated foods aimed at increasing convenience, extending freshness, and providing greater variety. Chilled foods may be considered as fresher and more natural than processed foods and more convenient due to longer shelf-life (than nonrefrigerated produce, for example) and ready-to-serve accessibility (compared to frozen foods, for example).

Many foods are refrigerated for direct consumption. Table 5.1 shows some typical food products that require refrigeration. Some foods require refrigeration immediately, while others require refrigeration only after the package has been opened by the consumer.

The primary purpose of refrigerating foods is to extend shelf-life by slowing down degradatory reactions and limiting microbial growth. Through reduction in rates of chemical, biochemical, and microbial kinetics, low-temperature storage can extend the shelf-life of fresh and processed foods. Typically, refrigerated storage means holding food in the temperature range of –1 to 8°C.

5.1 table Typical Foods Needing Refrigerated Storage

Dairy: milk, yogurt, cheese, cream, butter, etc.
Meats: beef, pork, chicken, turkey, seafood, etc.
Deli salads: macaroni salad, tuna salad, cole slaw, potato salad, etc.
Pasta (fresh)
Vegetables
Eggs
Salads: caesar salad, prepared salads, etc.
Dips, dressings, and sauces: mayonnaise, mustard, ketchup, etc.
Spreads: margarine, blends, etc.
Ready-to-eat meals: pizza, prepared lunches, etc.
Refrigerated dough products: cinnamon rolls, croissants, biscuits, etc.
Pastries and desserts: cakes, pudding, etc.
Fruit juices and drinks: orange juice, apple juice, etc.

Other factors besides low temperature may influence shelf-life of refrigerated foods. For fresh foods, these include the type of food and variety, the condition of the food at harvest (mechanical damage, microbial contamination, and degree of maturity), and the relative humidity of storage atmosphere (which, for example, can influence drying). For processed foods, factors affecting shelf-life include type of food, degree of microbial or enzyme destruction during processing, hygienic factors during processing and packaging, and the nature of the package (barrier properties).

In addition to retarding microbial growth, low temperature also limits the rate of chemical, biochemical, and physicochemical changes. For example, rates of lipid oxidation, nonenzymatic browning, sugar conversion, enzymic browning, and respiration reactions are reduced at low temperature. Refrigerated storage can slow development of off-colors or off-flavors, as well as changes in physical properties of foods, through the reactions mentioned before. However, some vitamin degradation still takes place even at low temperatures. The sum of all these effects results in extended shelf-life for refrigerated foods.

As an example of how shelf-life may be extended by refrigerated storage, consider milk. Milk is pasteurized by heating to about 65 to 70°C for a short period of time to destroy problem microorganisms. However, pasteurization does not destroy all microorganisms–milk is certainly not sterile. The remaining microorganisms grow and multiply at a rate dependent on the temperature of storage. If milk is left out at room temperature, it spoils in 2 to 3 days. Here, spoilage means that the microorganisms cause substantial chemical changes in the product so that both flavor and textural (for example, pro-

tein degradation) changes occur. When stored in the refrigerator at 5°C, growth of these microorganisms is considerably slower, and the shelf-life of milk can be up to 2 weeks. Processing conditions can dramatically change this situation. When milk is given more intense heat treatment, as with Ultra High Temperature (UHT) processing, most microorganisms in milk are destroyed, and the shelf-life is extended to several months.

However, not all foods have extended shelf-life when refrigerated. These products demonstrate some form of chilling injury. Some fruits and vegetables exhibit negative reactions to cold storage. For example, bananas turn brown quickly during refrigerated storage below 12°C, and citrus fruit exhibits brown spotting of the rind during refrigerated storage. Another common product that should not be stored in the refrigerator is bread, since the rate of staling is increased at low temperature.

The optimal storage temperature for maximum shelf-life depends on the type of food. Table 5.2 gives the range of optimal storage temperatures for a variety of foods. An extensive table of optimal refrigerated storage conditions is provided by Rao (1992). Fresh fish and meats should be stored at the lowest possible temperature (before freezing occurs) to maintain freshness. Other products–such as milk, cream, yogurt, salads, sandwiches, pasta, pizza, dough, and pastries–should be stored at temperatures less than 5°C to give maximal shelf-life. For other refrigerated products, such low temperatures are not absolutely necessary, and they can be stored at slightly warmer temperatures, up to 8 to 10°C. These foods include cooked meats, butter, margarine, hard cheese, and soft fruits.

While an optimal storage temperature exists for each food, it is unlikely that each food will always be stored at that optimal point. Refrigerated storage can be roughly broken into four phases: commercial storage, transport, retail storage, and home storage. Some foods, particularly processed foods requiring refrigerated storage, may be held for a period of days to weeks in commercial storage facilities. Temperatures here are usually at the optimal storage point for the product, since it is more likely (but not always) that only a single product is being stored. Product is then transported to the retail sector. Transportation in refrigerated trucks or railcars is extremely sophisticated, and excellent control of temperature is possible during shipping. However, periods of elevated temperature are often encountered, particularly during loading and unloading. Severe temperature swings may occur during these periods, with great damage to heat-sensitive product. Once at the retail outlet, the food is usually stored in large common refrigerators, where many different products are held at the same time, prior to stocking in refrigerated retail cabinets for consumers. In retail cabinets, optimal storage temperature may be difficult to maintain, as consumer access and convenience are also important factors to consider. Products removed

5.2 table Optimal Storage Conditions for Some Fruits and Vegetables

Food	Temperature (°C)	Relative Humidity (%)	Storage Life
Apricot	-0.5–0	90	1–2 wk
Banana	11.7–15.6	85–95	7–10 days
Bean (snap)	7.2	90–95	7–10 days
Broccoli	0	95	10–14 days
Blueberries	-1–0	90–95	2 wk
Cantaloupe	2–4	90–95	5–15 days
Carrot	0	98–100	4–6 wk
Celery	0	95	1–2 mo
Cherry (sour)	-1–0	90–95	3–7 days
Cherry (sweet)	-1	90–95	2–3 wk
Cucumber	10–13	90–95	10–14 days
Eggplant	7–10	90–95	7–10 days
Grapefruit	10–16	85–90	4–6 wk
Lemon	10–14	85–90	1–6 mo
Lime	9–10	85–90	6–18 wk
Lettuce	0–1	95–100	2–3 wk
Mushroom	0	90	3–4 days
Onion (green)	0	95	3–4 wk
Peach	-0.5–0	90	2–4 wk
Pepper	7.2	90–95	2–3 mo
Plum	-1–0	90–95	2–4 wk
Potato	3–10	90–95	5–8 mo
Spinach	0	95	10–14 days
Strawberry	-0.5–0	90–95	5–7 days
Sweet potato	10–12.8	85–90	4–7 mo
Tomato (ripe)	4.4–10	85–90	4–7 days
Watermelon	4–10	80–90	2–3 wk

From Frazier and Westhoff (1988) and Rao (1992).

from retail cabinets are transported to the home, where they are placed in the refrigerator. Substantial temperature fluctuations are likely to occur during this transportation process as well, since there is very little control over temperature. Thus, storage at optimal refrigerated temperature is unlikely to occur as a product passes through the distribution system and substantial damage to heat-sensitive products or microbial growth can occur.

For optimal shelf-life, refrigeration may be combined with other preservation technologies. Techniques such as controlled atmosphere storage or

vacuum packaging may enhance shelf-life of refrigerated foods. For example, shelf-life of several products stored either in air or a modified atmosphere are compared in Table 5.3. Also, in Table 5.4, recommended conditions for refrigerated and modified atmosphere storage of some fruits are provided (Zeuthen et al., 1990). Clearly, the use of modified atmosphere storage can significantly enhance shelf-life of many food products under refrigerated storage. Other hurdle technologies (microbial or chemical inhibitors, etc.) may also be implemented to slow rates of microbial, chemical, and biochemical processes.

In the United States, regulations from either the USDA (meat and poultry) or FDA (other foods) control manufacture, packaging, and storage of refrigerated foods. Specifically, refrigerated foods must be held at temperatures at or below 7.2°C (45°F), and processing measures for destroying or preventing growth of undesirable microorganisms must be adequate for the purpose. Refrigerated foods should also be marketed under refrigeration and should be clearly labeled as needing refrigeration. Processed foods that may become contaminated after opening should also be so labeled.

GENERAL PRINCIPLES OF REFRIGERATED STORAGE

For both fresh and processed foods, any or all of the following general steps or operations may be applied for production of refrigerated foods.

Pretreatment

Some foods are treated prior to cooling to refrigerator temperatures. Pretreatments are designed to enhance shelf-life, usually through reduction in the initial microbial content. For example, raw milk on the farm is cooled initially for transportation to the processing plant, where it then undergoes a pasteurization process to reduce bacterial counts. Pasteurized milk must still be refrigerated to allow shelf-life of 7 to 10 days. The extent of pasteurization primarily determines shelf-life of milk, with greater heat treatment resulting in longer shelf-life. Of course, other changes to the quality of milk are experienced when extended pasteurization (Ultra High Temperature [UHT] processing) occurs.

Preparation of fish and meat prior to refrigerated storage also ensures extended shelf-life due to reduction of initial bacterial counts. For example, poultry products must be dipped in antimicrobials (sulphites) to ensure extended shelf-life, even at refrigerated temperatures.

Table 5.3 Comparison of Shelf-Life of Products Stored in Either a Modified Atmosphere or Air (from Zeuthen et al., 1990)

Product	Optimal Gas Composition CO_2: N_2	Shelf-Life (days)	
		Air	Modified Atmosphere
French fries	50:50	<15	21
Pizza (ham)	20-60:80-40	<28	36
Vienna sausage	20:80	<20	≥ 32
Hamburger steaks (with cheese)	20:80	<14	35

Table 5.4 Recommended Temperature and Modified Atmosphere Storage Conditions for Some Fruits (from Zeuthen et al., 1990)

Fruit	Temperature (°C)	% O_2	% CO_2
Apple	0–4	2–3	1–5
Cherry	0	3–10	10–15
Chestnut	0	3	10
Citrus	5–15	10–15	5
Fig	0–5	5–10	15–20
Kiwi fruit	0	2	4–5
Nectarine	-0.5–0	2	5
Peach	-0.5–0	2	4–5
Pear	-1.5–5	1–6	0.5–4
Plum	0	2	5–12

Chilling Processes

Once the food has been prepared, it must be cooled to refrigeration temperature in some way. The choice of cooling unit depends primarily on the type of food, whether liquid, solid, or semisolid. Chilling can take place by either conduction, convection, radiation, or evaporative cooling. Radiation cooling has a place in food operations, for example in cooling tunnels for chocolate and confectionery. However, its application in general food processing is limited. Conduction heat transfer may be used when product geometry is suitable for contact with solid chiller elements. For example, plate freezers or chillers can be used for cooling slabs of beef or fish fillets with regular shape.

Most food chilling relies on convective heat transfer to cool the product. Coolant fluid either passes directly over the product (solid foods), or is in

indirect contact through a heat exchanger wall (liquid foods), to remove heat from the product. The rate of cooling is determined by the rate of heat transfer through the product itself and the rate of heat transfer from the product surface to the coolant medium. Parameters that influence the rate of heat transfer include the surface area for heat exchange, the temperature difference between product and coolant medium, the thermal properties of the food (i.e., thermal conductivity), and the degree of convective heat transfer due to coolant flow (convective heat transfer coefficient). Typical heat transfer coefficients for convective cooling vary from 5 W/m^2 °C for slow moving air to 500 W/m^2 °C for rapidly flowing water. The amount of heat to be removed depends on the initial temperature of the product, and any heat generation sources within the food (i.e., heat of respiration or phase changes). Cooling times and refrigeration loads can be determined using principles of unsteady-state heat transfer combined with energy balances on the chilling system.

The rate of cooling may influence product quality. In general, more rapid chilling results in longer shelf-life, particularly for foods where shelf-life is limited by microbial growth. If a food remains at high (or even room) temperatures for an extended time, the microbial population increases rapidly and the length of time to spoilage (shelf-life) decreases. Even if a product is being cooled at a slow rate, it remains at warmer temperatures for longer times, compared to rapid cooling. Thus, more microbial growth occurs for slower cooling, and it is good practice to chill foods as quickly as possible to limit microbial growth.

Chilling of Solid Foods. There are many cooling methods for solid foods, but the most common of these is blast chilling, or blowing cold air across the surface of either packaged or unpackaged product. Air coolers can be operated as either batch systems, where a single load of product is cooled at one time, or as continuous systems. In a continuous forced-air cooler, the product is usually conveyed through the system while cool air is recirculated across the product. Air is cooled by passing it across evaporator coils of a mechanical refrigeration system, and then is distributed to flow evenly across the product surface. Continuous cooling tunnels are used for many types of food products, including meats and baked goods. Cooling tunnels are designed so that the product remains within the system for the time required to cool to the desired temperature. For products that cool slowly, this requires extremely long tunnels or space-saving technologies like spiral chillers.

Solid foods can also be cooled by direct immersion into a coolant medium, such as ice or cold water. Spraying cold water onto a product is also used for rapid cooling. Vegetables such as celery, asparagus, peas, and corn

can be cooled in this way, as are some meats and poultry. Cooling cheese by direct immersion in brine is common practice in cheese plants. Efficient convective heat transfer results from direct contact with cooling water, since heat transfer coefficients are much higher than for moving air. However, not all foods can come in direct contact with water or other coolants. Direct-immersion systems can also be operated in either batch or continuous modes.

Other types of cooling systems for solid foods include direct-contact plate coolers, vacuum evaporative coolers, and cryogenic coolers using solid carbon dioxide or liquid nitrogen.

There are several concerns regarding chilling of solid foods. First, for unpackaged goods being cooled by air or vacuum evaporation, water loss can cause significant decrease in product quality. Precautions must be taken to ensure adequate protection against moisture loss, by maintaining proper air conditions so that drying is minimized. A second concern is the temperature at the product surface during cooling. Temperature of the coolant is limited by the surface temperature. On the one hand, low coolant temperatures give the most rapid cooling rate. However, low coolant temperature also means that the surface temperature is likely to go below the freezing point of the product and may potentially cause problems associated with surface freezing. A balance between these two effects is needed to ensure optimal product quality and maximal cooling efficiency.

Chilling of Liquid Food. Most liquid cooling systems involve indirect heat exchange systems where product flows through one side of a heat exchanger, and coolant, whether a primary or secondary refrigerant, flows on the other side. Heat is transfered by convection within the two fluids and by conduction through the metal wall of the heat exchanger. Heat transfer coefficients are determined by the relative magnitudes of convective and conductive heat transfer. Sometimes liquid foods are cooled in batch vessels or kettles, with coolant flowing through a jacket around the vessel. The principles of unsteady-state heat transfer govern time of cooling in this case.

Heat exchangers used for cooling liquid foods can be either plate, double tube, falling film (or surface) coolers, scraped surface, or shell and tube designs. Probably the most common type is the plate-and-frame design. Here, many plates are stacked on a frame, with spacing between plates and flow directions determined by rubber gaskets. Product to be cooled and coolant medium flow through alternate plates to give high heat exchange surface area for minimal space occupied on the plant floor. This heat exchanger also allows energy conservation or recovery techniques, where heat can be reclaimed from various process flows for cooling or heating.

Refrigerated Storage

Once a product has been cooled to storage temperature, its temperature must be maintained in a refrigerated storage area. Sometimes, however, chilling and refrigerated storage are accomplished in the same area. That is, some products are simply put into the refrigerated storage area when warm and allowed to cool to storage temperature before shipping. Thus, the refrigerated storage area must also perform cooling operations at times and must be designed accordingly.

Typically, foods are stored in refrigerated storage rooms kept cool by cold-air circulation. Product may be stacked on pallets (i.e., cheese), hung from ceiling hooks (as in the case of meats), or stored on shelves or in small cubicles for automated retrieval. Product transport within the refrigerated storage area may be completely automatic, based on computer-controlled robotic conveyances, or completely manual, where operators drive forklifts or other conveyance devices to pick up and select product for shipping.

Air in the refrigerated storage area is cooled using a mechanical refrigeration system, where air passed over the evaporator coils as a primary refrigerant (ammonia or freon) is evaporating. Proper air circulation is maintained using fans or blowers transporting cold air around the storage area through a series of ducts. Air recirculation is normally used to conserve energy, unless specific atmosphere requirements are needed.

For some products, the environment in the refrigerated room is also controlled to further ensure product quality. For example, apples are stored in a cold room with an atmosphere low in oxygen and high in carbon dioxide and nitrogen. This combination of cool temperature and modified atmosphere results in significant shelf-life improvement for apples. Such conditions are currently being applied to other products as well, including meat, poultry, and fish.

A refrigerated storage area must also account for any further changes in thermal energy of the product during storage. For example, fresh produce continues to respire even at low temperatures, generating heat from within, as does cheese, in which ripening reactions for flavor development are occurring during storage. The refrigeration system for the storage area must be able to remove this heat while maintaining constant temperature. The refrigeration system must also account for any thermal losses due to heat input through walls, windows, floor, and ceiling, and when doors are opened to warmer outside environs. Any heat inputs due to operation of mechanical equipment (i.e., forklifts) must also be considered. To design the refrigeration system, one must know the magnitudes of these energy terms, perform an energy balance on the entire system, and determine the

refrigeration requirement (in tons of refrigeration). This allows the size of the mechanical refrigeration system to be calculated.

Several factors, some of which have already been mentioned, must be controlled for efficient refrigerated storage. These include:

Temperature. Controlling temperature is critical for maximizing shelf-life, but what exactly does controlled temperature mean? For mechanical refrigeration systems, there is always some fluctuation in temperature due to automatic control and defrost cycles. Other sources of fluctuations might include opening and closing doors, changing heats of respiration within a product during storage, or heat inputs due to mechanical equipment. High air turnover rates (ventilation times) will help maintain uniform temperatures; however, temperature control within $\pm 1°C$ is usually satisfactory. Adequate control of air temperature usually means excellent control of product temperature, due to higher mass and higher specific heat of product. Relatively large fluctuations in air temperature may cause only small changes in product temperature, with the product surface seeing higher fluctuations than the product interior.

Air Circulation. Maintaining uniform temperature throughout the storage area requires adequate air circulation. Product should be stacked in such a way that adequate air flow exists for all material. This is especially important for products that are giving off heat of respiration or reaction (i.e., fruits and vegetables, and cheese). Proper air circulation, along with air temperature control, ensure that heat leaks have only minimal effect on product storage temperature.

Air Composition. Several factors may be important relating to air composition. First, moisture content of the air may have a negative impact on foods, as many foods have an optimal relative humidity for storage. Unpackaged produce must typically be stored at high relative humidities to prevent drying of the product. However, high relative humidities may result in rapid and extensive mold growth. Usually, only moderate control of air moisture is used for refrigerated storage. A second concern is presence of unwanted odors in refrigerated air. Since air is usually recirculated through these systems, negative odors may not be removed. In some foods, these odors are absorbed and cause significant off-flavors. Recirculation of air through activated-carbon filters removes most of these volatile odors. Finally, some products should be stored under controlled atmosphere storage, and gas composition managed to provide extended shelf-life. Systems for controlling nitrogen, carbon dioxide, and oxygen levels must be implemented under these circumstances.

Refrigerated Transport

From the commercial storage area, product is transported to the local market by either rail, truck, sea, or air, or through some combination of these forms of transportation. Most foods are transported by either truck or rail, unless special needs for rapid transit are recommended for best quality. Some highly perishable products may be transported by air–including strawberries, asparagus, and lobsters–where other techniques for storage are not appropriate. Since air transport is considerably more expensive than ground transportation, economics play a deciding role in which transport system is utilized. Sea transport is utilized for moving produce, under controlled temperature and atmosphere, from Australia and New Zealand to Japan, North America, and Europe. It is also an important aspect of the fisheries industry, where proper shipboard refrigeration is needed to maintain highest quality for fresh fish.

The primary function of refrigerated transport is to move product from either the point of harvest or a commercial storage area to the retail outlet, with no loss in product quality. Adequate refrigeration and air circulation must be maintained within the transport storage area to keep product temperatures near optimal. Temperatures should be neither too high nor too low. Whatever refrigeration system is used in transport vehicles, it must be appropriate to maintain refrigerated conditions for the duration of the trip. The refrigeration system must counter any heat losses occurring through the walls, floor, and ceiling of the transport vehicle, and be able to withstand periodic opening and closing of doors. In addition, the heat of respiration of fresh produce must also be removed by the refrigeration system. Optimal design of efficient and economic refrigerated transport systems must take these factors into consideration.

Refrigerated transport systems may be based on mechanical refrigeration units, eutectic plates, or direct expansion of liquid nitrogen.

Mechanical Refrigeration Systems. Most transport systems are based on mechanical refrigeration systems, where an enclosed refrigeration system, usually based on expansion of Freon, is contained within the mobile unit. The refrigeration system provides cooling through expansion of liquid Freon in an evaporator coil within the refrigerated environment, similar to operation of a home refrigerator or an air conditioner in an automobile. These systems can be operated directly from the vehicle's battery or from a separate generator on the storage unit, and are ideal for long-distance transportation in trucks and railcars.

Eutectic Plate Systems. Some transport systems utilize eutectic plate cool-

ing systems, especially for local distribution chains. A eutectic plate system is based on a frozen salt solution at its eutectic temperature (where water and salt form a single phase, or a solid solution). As the salt eutectic solution melts at its eutectic temperature, heat is removed from the environment and provides refrigeration. Typical salts used include potassium bicarbonate, potassium chloride, ammonium chloride, and sodium chloride, with eutectic temperatures ranging from −3 to −21°C. Air is circulated across the eutectic plates and into the refrigerated chamber to provide refrigeration during transport. The eutectic plates must be regenerated periodically by freezing in an external mechanical refrigeration system.

Liquid Nitrogen. Refrigeration through spraying and direct expansion of liquid nitrogen has been used for refrigerated transport systems. Here, liquid nitrogen is sprayed directly into the refrigerated environment to provide cooling due to latent heat of vaporization. Use of direct liquid nitrogen expansion systems is limited due to higher operating costs compared to mechanical refrigeration systems.

Retail Storage

Once refrigerated products are brought into a retail outlet, they are usually stored for a short time in a large, common storage area prior to stocking in refrigerated cabinets for sale. Temperature in these refrigerated rooms is normally maintained by circulating cold air that has been cooled by passage across evaporator coils of a mechanical refrigeration system. Normally, liquid ammonia or Freon is used as the primary refrigerant to cool the air for circulation.

Stocking of product in refrigerated cabinets is a potential cause of significant temperature fluctuations. Product must be removed from the storage area and stacked in retail cabinets in such a way that the food does not remain at room temperature for very long. Product stacked in cabinets must also be rotated so that the oldest product is selected first by the consumer. This ensures that no product remains in the cabinet for longer than desired for optimal quality. Storage location within a retail cabinet is also an important factor governing temperature, with variability between locations within the cabinet of up to 5°C. Cabinet locations closest to the evaporator coils of the refrigeration system and farthest from the entry point maintain lowest temperatures. Clearly, temperature distributions within the cabinet can have a significant impact on shelf-life of refrigerated foods.

Retail storage cabinets must maintain product at optimal temperature to maximize shelf-life. However, these cabinets often contain a variety of

foods with different optimal storage conditions. Thus, not all foods will experience optimal conditions. Another primary purpose of retail cabinets is to provide convenient visibility and access for the consumer. This often means that cabinets are not covered, and refrigeration is continually lost to the environs. Also, lighting requirements for good food visibility generally mean that additional refrigeration is required. Thus, the refrigeration system, usually a mechanical refrigeration system based on Freon contained within the cabinet, must accommodate heat losses to the environs as well as heating due to lights.

Refrigerated Cabinets for Food Service

At institutional cafeterias, restaurants, and other food service establishments, refrigerated cabinets serve similar duties. For cafeterias in particular, refrigerated cabinets must function in the same manner as retail cabinets. They must maintain refrigerated conditions within the cabinet while providing good visibility and consumer access. Many different types of refrigerated cabinets are available for these purposes.

Home Refrigeration

Once product is brought into the consumer's house, refrigerated foods must be separated and quickly placed in the home refrigerator. Extended periods at warm temperatures, either during transport to the home or at room temperature prior to storage, can cause significant deterioration of shelf-life. Home refrigerators function on the same basic principle as many retail cabinets, where a mechanical refrigeration system based on Freon is enclosed within the unit. Evaporator coils, now usually embedded in the walls of the refrigerator and attached freezer, provide cooling for the space within. Condenser coils on the outside back of the unit provide recycle of Freon gas for the refrigeration system.

The requirements of a home refrigerator are similar to those of retail refrigerated cabinets. The system must supply refrigeration to counteract heat losses through the walls and any heat allowed in during door openings. Convenient access to the contents of the refrigerator must be accommodated in the design of the system and the refrigeration unit.

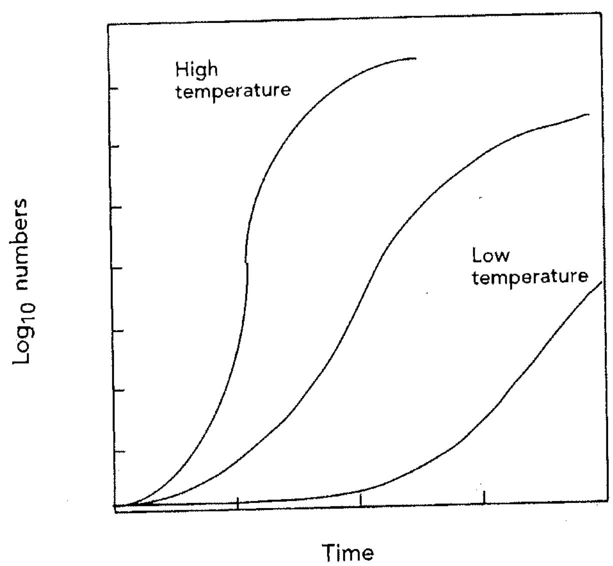
Within the refrigerated space, temperatures are usually kept rather high, above 6 to 8°C. However, there may be additional storage areas where different temperatures may be maintained, through a combination of design and insulation. For example, there may be produce or meat drawers where lower temperatures may be maintained. An interesting example of

this is the butter drawer in refrigerators in New Zealand, where butter is maintained at slightly higher refrigeration temperature to ensure its spreadability when used directly from the refrigerator.

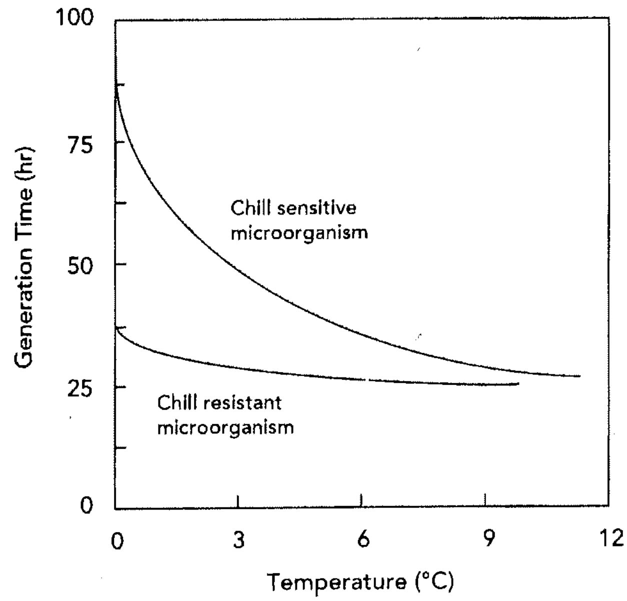
CONTROL OF MICROBIAL GROWTH DURING REFRIGERATED STORAGE

The effects of temperature on microorganism growth has been well documented. Typically, low temperatures slow the rate of each step in the microbial growth cycle, as seen schematically in Figure 5.1. Lower temperatures result in a significantly longer lag phase prior to population growth, and significantly slower growth in the exponential phase. In addition, the generation time, or time between formation of a daughter cell and its division into two new cells, is reduced at lower temperature, as seen in Figure 5.2.

Many microorganisms do not grow under refrigeration temperatures (less than 7°C). However, there are also many, including some pathogens, that do. For example, *Clostridium botulinum* type E reportedly can grow at temperatures as low as 3.3°C; *Listeria monocytogenes* can grow at 3°C; and *Yersinia enterocolitica* can survive and grow at temperatures as low as 0°C (Frazier and Westhof, 1988). It is for this reason that refrigeration must be



5.1 figure Generalized effect of temperature on microorganism growth cycle.



5.2 figure Generalized effect of temperature on microorganism generation time.

combined with some other preservation technology to ensure commercial sterilization. Refrigeration by itself does not guarantee that a food is safe from pathogenic microorganisms.

Probably the most important aspect of microbial growth in refrigerated foods is the minimum growth temperature. This may be defined as the lowest temperature at which growth of a microorganism can occur. Minimum growth temperatures for some microorganisms are listed in Table 5.5. These values must be used with caution, however, as they may depend on the experimental parameters used in their determination. Minimum growth temperatures are found by determining the hold temperature at which the microorganism does not grow, or where the lag phase is essentially infinite. Thus, the time of observation when measuring minimum growth temperature is crucial for accurate determinations. In addition, many process factors influence this minimum growth temperature, and each food must be considered somewhat independently.

External factors that influence growth of microorganisms in refrigerated foods include:

Initial Microorganism Population. The type and number of microorganisms present during refrigerated storage is important in determining shelf-

5.5 table Minimum Temperature for Growth of Some Microorganisms

Organism	Minimum Temperature (°C)
Aeromonas hydrophilia	1–5
Bacillus cereus	7
Campylobacter jejuni	27
Clostridium botulinum (E)	3.3
Clostridium perfringens	20
Escherichia coli	4
Listeria monocytogenes	3
Plesiomonas shigelloides	8
Salmonella	5.2
Staphylococcus aureus	10
Vibrio parahaemolyticus	5
Yersinia enterocolitica	1–7

From Frazier and Westhoff (1988).

life in refrigerated foods. In general, more microbes present initially results in decreased storage life.

Characteristics of the Food. Factors such as water activity, pH, nutrient content for microbial growth, and preservative content influence shelf-life of refrigerated foods. Low pH, low water activity, and proper formulation can lengthen refrigerated storage time of foods.

Effects of Processing. Many processing steps affect refrigerated storage time. These include the temperature and time for refrigerated storage, any pretreatment or holding times at elevated temperatures, previous heat treatment for microbial destruction (i.e., pasteurization), pH adjustment, drying (reducing water activity), addition of preservatives, and storage atmosphere.

Refrigerated storage is focused primarily on spoilage bacteria; however, pathogens may also be present and multiply in certain instances. Spoilage bacteria that may be of concern in refrigerated foods are listed in Table 5.6, while pathogens that can survive under refrigerated conditions are listed in Table 5.7.

The effects of a number of storage parameters, including refrigeration temperature, on microbial populations can be predicted through use of microbial growth prediction models. While predictive modeling in microbiology is not new, more recent models use kinetic parameters for microbial growth and survival to predict microbial populations under a wide variety of conditions. Typically, these models rely on a large database relating mi-

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5.6 table Spoilage Bacteria of Concern in Refrigerated Foods

Classification	Minimum Temperature (°C)	Typical Foods
1. Gram-negative rod-shaped bacteria	– 3–0	Fresh foods
Acinetobacter		meat
Aeromonas		poultry
Alcaligenes		fish
Alteromonas		dairy
Flavobacterium		
Moraxella		
Pseudomonas		
Shewenella		
Virbio		
2. Coliform/enteric bacteria	– 2–8	Various
Citrobacter		
Escherichia		
Enterobacter		
Klebsiella		
Proteus		
Serratia		
3. Gram-positive spore-forming bacteria	0–5	Various
Bacillus		
Clostridium		
4. Lactic acid bacteria	0–5	Various
Lactobacillus		
Streptococcus		
Leuconostoc		
Pediococcus		
5. Other bacteria	Varied	Meats
Arthobacter		
Corynebacterium		
Kurthia		
Micrococcus		
6. Yeasts and moulds	< 0	All foods
Yeasts:		
Candida		
Debaryomyces		
Hansenula		
Kluveromyces		
Rhodotorula		
Saccharomyces		
Torula		
Zygosaccharomyces		

Table 5.6 continued next page

Table 5.6. Spoilage Bacteria *(Continued)*

Classification	Minimum Temperature (°C)	Typical Foods
Molds:	< 0	All foods
Aspergillus		
Cladosporium		
Geotrichum		
Mucor		
Penecillium		
Rhizopus		
Thamnidium		

From Walker (1992).

5.7 table Pathogenic Bacteria of Concern in Refrigerated Foods

Classification	Minimum Growth Temperature (°C)
Listeria monocytogenes	– 0.4
Yersinia enterocolita	– 1.3
Aeromonas hydrophila	– 0.1–1.2
Bacillus cereus	1
toxin production	4
Clostridium botulinum	
proteolytic	10–12
nonproteolytic	3.3–5
Salmonella spp.	5.1
Eschirichia coli	7.1
Staphylococcus aureus	7.7
toxin production	14.3
Clostridium perfringens	> 10
Campylobacter spp.	> 10

From Walker (1992).

crobial kinetics to external (temperature, etc.) and internal (pH, salt content, nutrient content, water, etc.) parameters. A wide range of experimental conditions are used to determine kinetic parameters, which are then modeled in some way for use in predicting microbial behavior at different conditions. The model may be used for interpolation between existing data points or for extrapolating to wider ranges than can be experimentally studied. Extrapolation of these data must be done with care, as different

mechanisms may apply at different conditions and cause large errors in a predictive model.

Predictive models may use Arrhenius kinetics for describing temperature dependence, and polynomial models for predicting effects of different parameters, although many different types of models based on different kinetic models have been proposed. Due to the relative newness of this field, there is no consensus on the "best" model for use. In general, the better and broader the database of kinetic parameters, the more reliable the predictive model.

Microbial predictive models may be used in several ways. For example, they may be used to evaluate microbial stability in different formulations. A food product developer need only look at the predictive model to determine whether a given formulation will be microbially stable, or prone to microbial growth. Conversely, predictive models may be used to determine whether deviations in a formulation (due to process upsets, for example) will cause microbial problems and can be used in conjunction with HACCP programs. Specific to refrigerated foods, these models can predict the effects of temperature fluctuations, or poor refrigerated storage, on the microbial population in the product. This leads to estimates of shelf-life under varying storage conditions for a wide variety of product formulations. Clearly, this is a powerful tool for the food product developer. Thus, these models will continue to improve in the future and their use will expand accordingly.

DETERIORATION OF PRODUCT QUALITY

Many chemical, biochemical, and physical changes occur in refrigerated foods during storage, leading to loss of product quality. In many instances, these reactions, rather than microbial growth, limit the shelf-life of refrigerated foods. In general, the rate of these reactions decreases with temperature, although there are some significant exceptions to this rule.

Chemical Reactions

The same chemical reactions that affect shelf-life of all foods also apply to refrigerated foods. However, rates of these reactions are depressed at low temperatures, providing additional shelf-life. These reactions include:

Lipid Oxidation. In meats, poultry products, dairy products, and some fish, as well as many other processed foods containing fats, lipid oxidation is a significant quality factor during extended refrigerated storage. Lipid oxidation causes a characteristic oxidized flavor, or rancidity, through a complex series of reactions. Degree of unsaturation of fatty acids, their availability,

and the presence of activators or inhibitors are primary factors affecting the rate of lipid oxidation. Lipid oxidation can be prevented or inhibited using the following techniques: addition of some antioxidants or inhibitors, modified atmosphere storage (exclusion of oxygen), or vacuum packaging. As with all chemical reactions, the rate of lipid oxidation decreases with temperature. However, lipid oxidation rates in corn oil, for example, were retarded by only a factor of about 2 at refrigerator temperatures (4°C), as compared to room temperature (25°C) (deMan, 1990).

Maillard Browning. This complex chemical reaction between reducing sugars and proteins, leading to brown discoloration, may also occur at refrigerated temperatures. However, the rate of Maillard browning is significantly reduced at low temperature (by a factor of 2 to 3 in model systems), and other negative quality factors are usually more important to shelf-life of refrigerated foods.

Biochemical Reactions

Enzymes are efficient catalysts of biochemical reactions. Their presence in foods may be endogenous, where they appear naturally in a raw material, or exogenous, where they are added as an aid in food processing or as a result of contamination from other products or components. Enzymes participate in several reactions that may have negative impact on storage of refrigerated foods. These include:

Enzymic Browning. Enzymic browning occurs in fruits and vegetables after bruising or process preparations, such as cutting, peeling, or slicing. Phenolases contained within the tissue react with phenolic compounds in the presence of oxygen to produce a yellowish-brown pigment. The rate and extent of browning depends on the enzyme content, the type of product, pH, availability of oxygen, packaging conditions, and presence of inhibitors. Vacuum packaging or modified atmosphere packaging, and addition of inhibitors such as sulphites, citric acid, or ascorbic acid, can greatly reduce the effects of browning. Typically, enzyme reactions are reduced at low temperature.

Glycolysis. In living tissue, breakdown of glycogen is an important aspect of cell function and structure. After harvest or slaughter, this process still takes place, but changes in oxygen content direct this reaction to different end points, which cause breakdown of tissues and softening of structure, among other things. As with all biochemical reactions, the rate of glycolysis

is decreased at refrigeration temperatures, and physical changes associated with continued ripening are slowed.

Proteolysis. Proteases present in foods can alter flavor and texture of many products, including meat and fish, dairy products, and cheese. These enzymes attack protein matter in the food, breaking them down into peptides or shorter chain amino acid sequences. Many of these peptides contribute greatly to flavor changes during storage, while stiffness or texture may also be affected. In meats, for example, proteolysis is in part responsible for softening of tissue after slaughter, known as conditioning. This process may take place over a 2- to 3-week period in refrigerated storage. In cheese, proteolysis is thought to contribute to generation of characteristic flavors through release of peptides from casein.

Lipolysis. Lipases, whether already present or added as part of a product formulation, catalyse hydrolysis of triacylglycerols into fatty acids and other glyceride breakdown products (mono- and diglycerides). Since many fatty acids have characteristic flavors and odors, some of them unpleasant, lipolysis causes loss of product quality. An exception to this occurs in certain types of cheeses (i.e., Roquefort, Parmesan), where these lipid breakdown products enhance the flavor of the final product after ripening.

Physicochemical Reactions or Processes

Product quality may be affected through chemical and biochemical reactions or purely physical processes involving components of a food product. Chemical and biochemical reactions can often lead to changes in physical properties as well, such as softening of fruits and vegetables during ripening. Purely physical processes that might influence storage of refrigerated foods include:

Component Migration. In many products, migration of components, whether into or out of the food entirely or between structural elements of the food, can cause significant changes to product quality. Probably the most important food component, and one of the most mobile, is water. Foods may either pick up or lose moisture from the environment, depending on storage conditions and product characteristics. Typically, water activity is used to determine whether the product loses or gains moisture when in contact with air of certain relative humidity, although recent advances in this field suggest that the parameter of primary concern is molecular mobility (Fennema, 1996). Nevertheless, moisture loss (or drying)

occurs when the vapor pressure of water in the food is higher than that in the air, and the food gains moisture when the air has a higher water vapor pressure. Moisture migration between structural elements in a food, as in pizza crust and tomato sauce in a refrigerated pizza, can also occur and cause loss of product quality. The rate of moisture migration depends on the differences in water activity or vapor pressure, which are a function of temperature. Refrigerated storage slows down the rate of moisture migration between structural elements in a food but may actually enhance rates of evaporation due to the lower vapor pressure of cool air. Appropriate packaging (vacuum packaging and moisture barriers) can greatly reduce rates of drying of refrigerated foods.

Phase Changes. In some products, phase changes occurring slowly over time can cause loss of product quality due to associated physical changes. For example, staling of bread is thought to result, at least in part, from retrogradation of starch. Retrogradation involves slow crystallization of elements of the starch molecule and is thought to lead to firming of the bread matrix. At refrigerated temperatures, this process occurs more rapidly than at room temperature due to the increased driving force for crystallization. Other examples of phase changes influencing storage life in refrigerated foods include blooming of chocolates and hardening of butter due to lipid crystallization at low temperatures.

Nutritional Changes in Refrigerated Foods

Despite the general decrease in reaction rates at low temperatures, significant nutrient loss may still occur. Of particular importance are decreases in sensitive vitamins, such as vitamin C and the B vitamins. Typically, little change in nutritional content of proteins, lipids, or carbohydrates occurs solely due to storage at refrigerated temperatures. Other chemical or biochemical reactions might, however, reduce these components. For example, lipid oxidation reduces triacylglycerols to fatty acids, while browning reactions utilizing proteins can reduce the nutritional content.

Vitamin C is an especially labile vitamin in fresh produce, and even storage at refrigeration temperatures does not completely eliminate its degradation. However, since vitamin C degradation is related to enzyme processes, the rate of degradation is reduced at refrigerated temperatures. The extent of vitamin C degradation depends on the variety of produce (pH, water content, enzyme content, etc.), the atmosphere environment, and temperature, as shown in Table 5.8. Typically, low O_2 content in the atmosphere reduces vitamin C losses during refrigerated storage, and more humid environments fa-

vor vitamin retention (Bognar et al., 1990). Under ambient storage conditions, vitamin C losses of up to 50% per day have been reported for sensitive produce like spinach. For refrigerated storage, values less than 10% are more common, depending on the conditions of storage. In oranges and pineapple, vitamin C loss is minimized at storage temperatures of 10°C and increases at either higher or lower temperatures (Table 5.8).

ESTABLISHING SHELF-LIFE IN REFRIGERATED FOODS

Many factors affect storage life in refrigerated foods. In order for a food manufacturer to specify a shelf-life for a product, the effects of these parameters must be understood and controlled. These factors include the nature and type of raw materials, product formulation and assembly, any processing steps involved in production, the hygienic nature of those processing steps, package material and integrity, storage and distribution conditions, and, finally, how the product is handled by the consumer.

Raw materials vary considerably in shelf-life, which is affected by their initial microbial population and how this population responds to different growth environments, and the influence of other physicochemical reactions. Some products, like fruits and vegetables, have low initial microbial counts and do not spoil easily from microbial contamination, but rather

5.8 table Degradation of Vitamin C During Refrigerated Storage of Fruits and Vegetables (from Zeuthen et al., 1990)

Product	Initial Concentration (mg/100 g)	Losses (%/day) [a]		
		0–2°C [b]	4–8°C [c]	16–24°C [d]
Apple	12	0.1–0.5	–	3.0–8.0
Brussel sprouts	114	–	5.0	22.0
Caulifower	73	0.1–0.2	0.1–7.0	7.0–14.0
Cherry	15	–	18.0–25.0	18.0–25.0
Kale	105	0.5–4.4	–	20.0–23.0
Orange	50	26.0	10.0	16.0–20.0
Peas	25	1.0–2.0	2.0–6.0	11.0–13.0
Pineapple	19	18.0	10.0	17.0
Potato	17	–	0.1–0.6	–

[a] Storage time of 2 to 21 days.
[b] Storage room at 76–98% relative humidity (RH).
[c] Storage in refrigerator at 70–90% RH.
[d] Storage room at 50–70% RH.

spoil through physical and chemical ripening processes. Other products, such as milk, contain sufficient microbial population so that shelf-life is primarily limited by growth of these spoilage bacteria. When determining shelf-life of a product, whether a fresh produce item or a processed combined food, the attributes of concern in the raw materials should be well documented to prescribe rigid ingredient specifications. Any variability in these specifications may result in variability in shelf-life.

Product formulation and assembly is another important factor in shelf-life determination. Proper formulation is required to minimize negative physicochemical reactions that shorten shelf-life. Some of the natural variability in raw materials may be accommodated through proper formulation, thereby providing a consistent product with a given shelf-life. The manner in which a product is arranged may also influence shelf-life, as in complex foods with significantly different materials in direct contact. Water migration between components of different water activity is a common factor limiting shelf-life of foods, which occurs even at refrigerated temperatures. Proper formulation and assembly can minimize these shelf-life problems, for example through use of water-barrier films between components.

The initial microbial content can be significantly altered by processing conditions. Proper pasteurization of milk reduces the population of spoilage bacteria to the point where shelf-life is increased with minimal changes in product quality. Improper pasteurization or postprocess contamination can significantly decrease shelf-life. Blanching of vegetables is necessary to inactivate enzymes that limit shelf-life of canned products. Proper hygiene in the processing plant is also critical to maintaining shelf-life. Poor hygiene results in contaminated foods that significantly decrease shelf-life, as well as posing health risks.

One of the most important concerns in maximizing shelf-life is using the best packaging possible. An excellent product with potential for extended shelf-life can be ruined through use of improper packaging. Appropriate barrier properties for packaging films must be determined for each product. Limiting transfer of moisture, oxygen, and other gases, as well as limiting light, can significantly increase shelf-life. For example, the shelf-life of hard candies that are extremely hygroscopic can be increased using appropriate packaging material with high-moisture barrier properties.

From previous discussion in this chapter, the importance of temperature and time on the kinetics of negative quality reactions is clear. Each product has its own optimal storage conditions at which shelf-life is maximized. The rate of reactions and physical changes at temperatures other than optimal must be known in order to predict shelf-life under conditions of normal storage and transportation. By combining temperature/time pro-

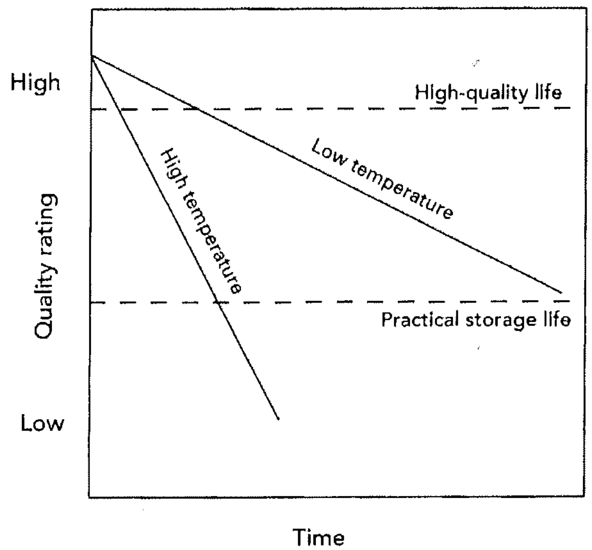
files for typical storage and distribution of a product with the specific reaction rates for changes in that product, an accurate assessment of shelf-life can be determined.

One final factor that influences shelf-life, which a food manufacturer has only limited control over, is consumer handling. Improper handling during transport to the home and then within the home can destroy shelf-life. The time between when the consumer removes the product from the refrigerated retail cabinet to when he or she places the product in the home refrigerator is extremely variable and uncontrollable. Yet this time may have significant influence on storage life of the product. Even when the product is in the home refrigerator, significant variability can occur, as temperature in these units is not consistent or stable.

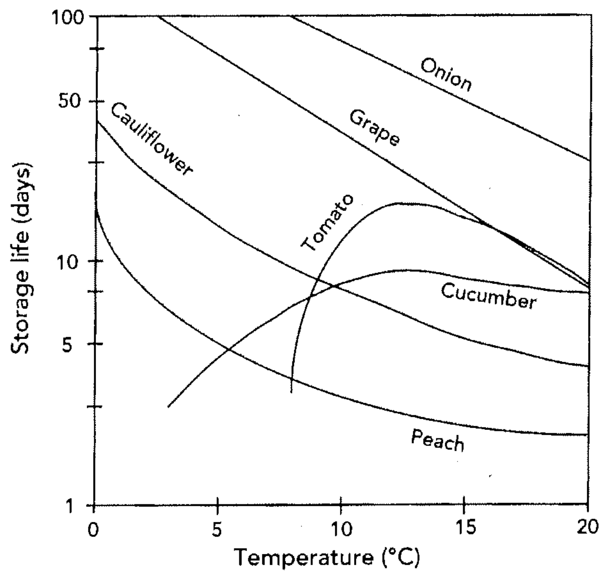
Predicting Shelf-Life of Refrigerated Foods

Considerable thought and energy has gone into approaches for determining shelf-life of foods. While some advances have been made to scientifically predict shelf-life, there are many variables to consider, and real progress is difficult. Many times, food manufacturers rely on experience with related food products to estimate shelf-life of new products. Probably the best method for accurate prediction of shelf-life is a system that mimics as close as possible the actual product during typical storage and distribution. A series of storage studies with actual product following typical storage and distribution conditions for temperature and time, coupled with some measure of end point of shelf-life, can provide an accurate assessment of shelf-life. End point of shelf-life can be determined by either analytical techniques, physical measurements, or sensory evaluations. Ultimately, shelf-life must be related to the loss of acceptability to the consumer.

Quality plots, such as shown in Figure 5.3, are often used to determine shelf-life. For storage of a food product under specific conditions, the quality change with time is measured according to either sensory evaluation, microbial content, or some measure of physical characteristic (i.e., color). Highest quality may last only a brief time, while adequate quality remains for significantly longer shelf-life. In most food products, the rate of change of quality with time increases as storage temperature increases, as shown in Figure 5.3. However, not all food products show this behavior. The effect of storage temperature on shelf-life of a variety of fruits and vegetables is shown in Figure 5.4. Cucumbers and tomatoes have optimal temperatures of storage in the range of 12 to 14°C, which is above the normal temperature of most home refrigerators in the United States. Below



5.3 figure Change in quality with time during refrigerated storage.



5.4 figure Storage life at different temperatures for some fruits and vegetables (from Bogh-Sorensen, 1990).

12 to 14°C, the shelf-life of cucumbers and tomatoes decreases with decreasing temperature.

Actual storage studies at typical storage conditions may not be the best approach for determining shelf-life, however, particularly for foods with long shelf-lives. The long times required to finish these tests does not allow for rapid product entry into the market. Some companies choose to use accelerated storage studies, usually at elevated conditions of temperature and relative humidity, to predict approximate shelf-lives. These are particularly useful for products with long shelf-lives. Since most refrigerated foods do not fall into this category, with few exceptions, accelerated storage studies are not seriously considered for this category.

To accurately assess shelf-life of a refrigerated food product, the following information must be known. First, the rate of the primary factors negatively influencing shelf-life–whether microbial, physical, or chemical–must be known over the range of temperatures of importance for refrigerated storage. This would probably range from 0 to about 15 to 20°C to ensure that any temperature spikes during storage could be accounted for. Second, typical storage temperatures and conditions should be determined for the product. What does a typical temperature/time profile look like for this product going through normal distribution channels? Finally, some measure of end point of shelf-life must be determined, using analytical, physical, or sensory techniques. Shelf-life can then be determined by combining the kinetics of the reactions for negative quality factors with temperature-time profiles to predict when the specific end point for the product has been reached.

For many foods, use of Arrhenius activation energy kinetics is satisfactory for describing temperature dependence of reactions that decrease shelf-life, whether microbial, chemical, biochemical, or physicochemical. For refrigerated foods, however, the applicability of the Arrhenius expression over cool temperatures has been questioned (Williams, 1990). Instead, it has been suggested that kinetics based on a square-root relationship apply to reactions at refrigerated temperatures. The equation relating kinetics of spoilage reactions to storage temperature is given as:

$$\sqrt{r} = b(T - T_0) \tag{5.1}$$

where r = reciprocal of time taken to achieve a specific increase in spoilage factor (i.e., increase in microbial population by 2 orders of magnitude)

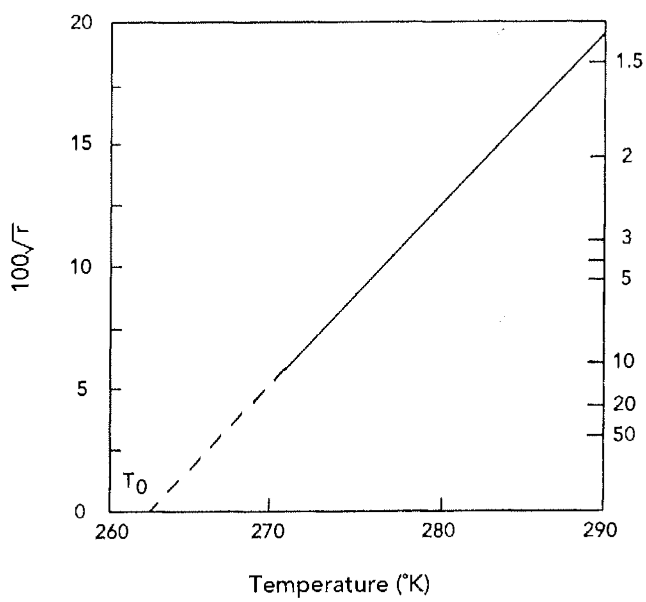
b = regression coefficient

T = absolute temperature

T_0 = temperature where reciprocal time goes to zero, or time for infinite multiplication of microbial population

A typical plot of Eq. (5.1) is shown in Figure 5.5. To use Eq. (5.1), the time to reach spoilage–whether due to microbial, chemical, biochemical, or physicochemical reaction–must be measured at several different temperatures. A regression on square root of r with temperature gives values for b and T_0. Once this equation has been defined for a food product, the maximum storage temperature to yield a desired shelf-life can be found, or the shelf-life at a given storage temperature can be determined. This equation has been found to hold for spoilage processes such as microbial growth in meats, cheese, pasta salads, and refrigerated pizzas, and browning of prepared vegetable and pasta salads (Williams, 1990).

From a process engineering standpoint, predicting shelf-life requires knowledge of kinetics of the reaction or mechanism that causes end of shelf-life, the effect of temperature on these kinetics, and a measure for the end point of shelf-life. With this information, shelf-life for any storage temperature/time profile can be calculated. However, data for this type of calculation are difficult and time consuming to obtain, require sensory panels



5.5 figure Generalized square-root plot for end point of shelf-life in refrigerated foods, where r represents time to endpoint based on spoilage factor.

to determine end point of shelf-life, and are seldom used in determining shelf-life of foods.

Temperature/Time Indicators

The use of indicators to follow temperature fluctuations during refrigerated storage for products has been recommended. Many types of indicators are available. The best system for shelf-life prediction would have a data (temperature) logger associated with the product during shipping and storage that would then be plugged into a computer to yield actual temperature/time data. This is not as simple as it sounds, however, since the temperature trace depends on many factors other than the actual environment conditions--for example, where the tracer is located in a package or container, and the rate of heat transfer into the tracer element may influence the temperature/time profile measured. Nevertheless, such tracer elements would allow much better prediction of shelf-life, if cost were not a concern.

Inexpensive temperature/time indicators show only the maximum temperature, or whether the product experienced a temperature above a certain maximum. For example, for especially heat-sensitive foods, a temperature of 10°C may be used to indicate that the product has experienced a heat shock that might have negative impact on product quality and safety. More sophisticated indicators, using irreversible polymer-reaction color changes, actually integrate the temperature profile to show the cumulative effects of elevated storage temperature. When the indicator reaches a certain color or shade, the consumer knows that the product has experienced elevated temperatures that might negatively impact product quality or safety.

Use of these indicators for refrigerated foods, however, is no guarantee that all bad product will be caught in this way. The many other factors influencing shelf-life (i.e., package integrity, quality of raw materials, hygienic processing) also affect quality of a specific product, and are not accounted for using these indicators. Thus, manufacturers have been hesitant to utilize these indicator devices as an extra expense that does not necessarily guarantee high-quality product at all times.

FUTURE DEVELOPMENTS

Use of refrigerated foods is likely to expand in the near future. Convenient and nutritious foods that require refrigeration either after opening the package or during the entire shelf-life will certainly continue to be developed as processors seek to expand existing product lines or open new lines.

Several areas or aspects of refrigerated storage will see development over the next few years. These include:

1. *Increased use of combined technologies for enhancement of shelf-life.* Controlled atmosphere storage, irradiation of foods, addition of natural bacteriocins as additional microbial hurdles, and use of time/temperature indicators will all enhance shelf-life of refrigerated foods;
2. *New packaging technologies.* Improved shelf-life of refrigerated foods may come through control of internal atmosphere conditions. New packaging may provide environmental advantages for package disposal.
3. *New products for health and convenience.* A general increase in the number of refrigerated foods providing a wider variety of convenient and healthful foods is expected in coming years.

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